

Woven from weirdness

The true origins of space-time, the backdrop to reality, are hidden in the quantum realm, writes physicist **Sean Carroll**

LET'S say you want to meet a friend for coffee. You have to tell them where you are going to be – your location in space – but you also need to let them know when. Both bits of information are necessary because we live in a four-dimensional continuum: three-dimensional space and everything within it, from steaming coffee machines to stars exploding in faraway galaxies, all happening at different moments of one-dimensional time.

“Space-time” is simply the physical universe inside which we and everything else exists. And yet, even after millennia living in it, we still don't know what space-time actually is. Physicists have strived to work it out for more than a century. In recent years, many of us have been trying to figure out what might be the threads from which the fabric of reality is woven. We have ideas, each with its own selling points and shortcomings. But for my money, the most exciting one is the most surprising.

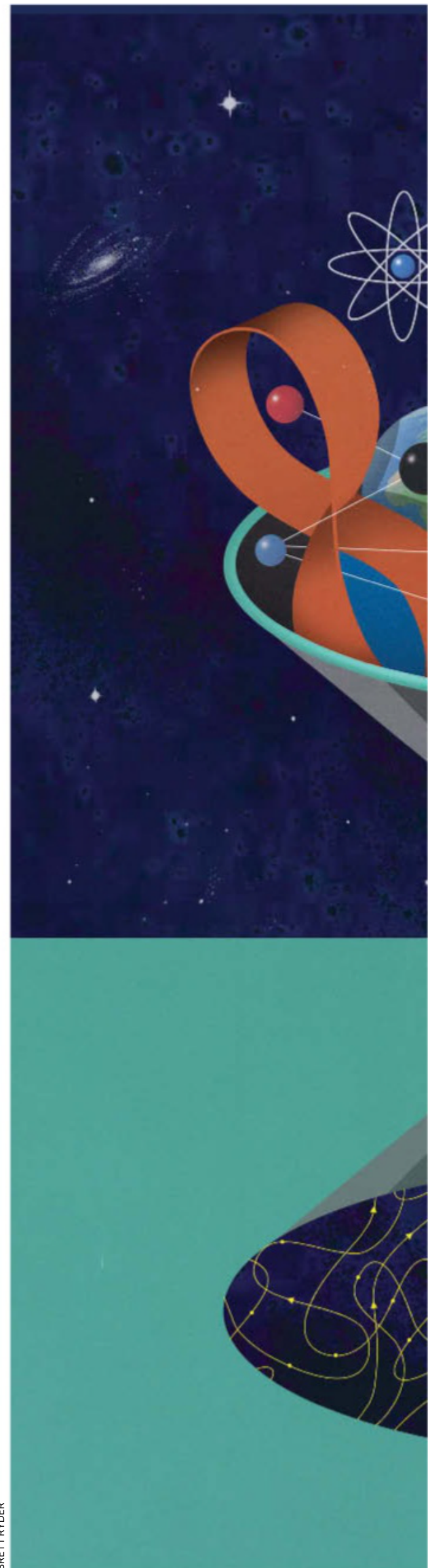
It is the idea that space-time emerges from a weird property of the quantum world that means particles and fields, those fundamental constituents of nature, can be connected even if they are at opposite ends of the universe. If that is correct, we might finally have found a bridge between the two irreconcilable totems of physics, placing us on the threshold of a theory of quantum gravity. We would also have the

most startling demonstration yet that the world we see isn't the world as it is – that there is always “something deeply hidden”, as Albert Einstein put it – and that the only way to understand the fundamental nature of reality is by confronting quantum mechanics head-on.

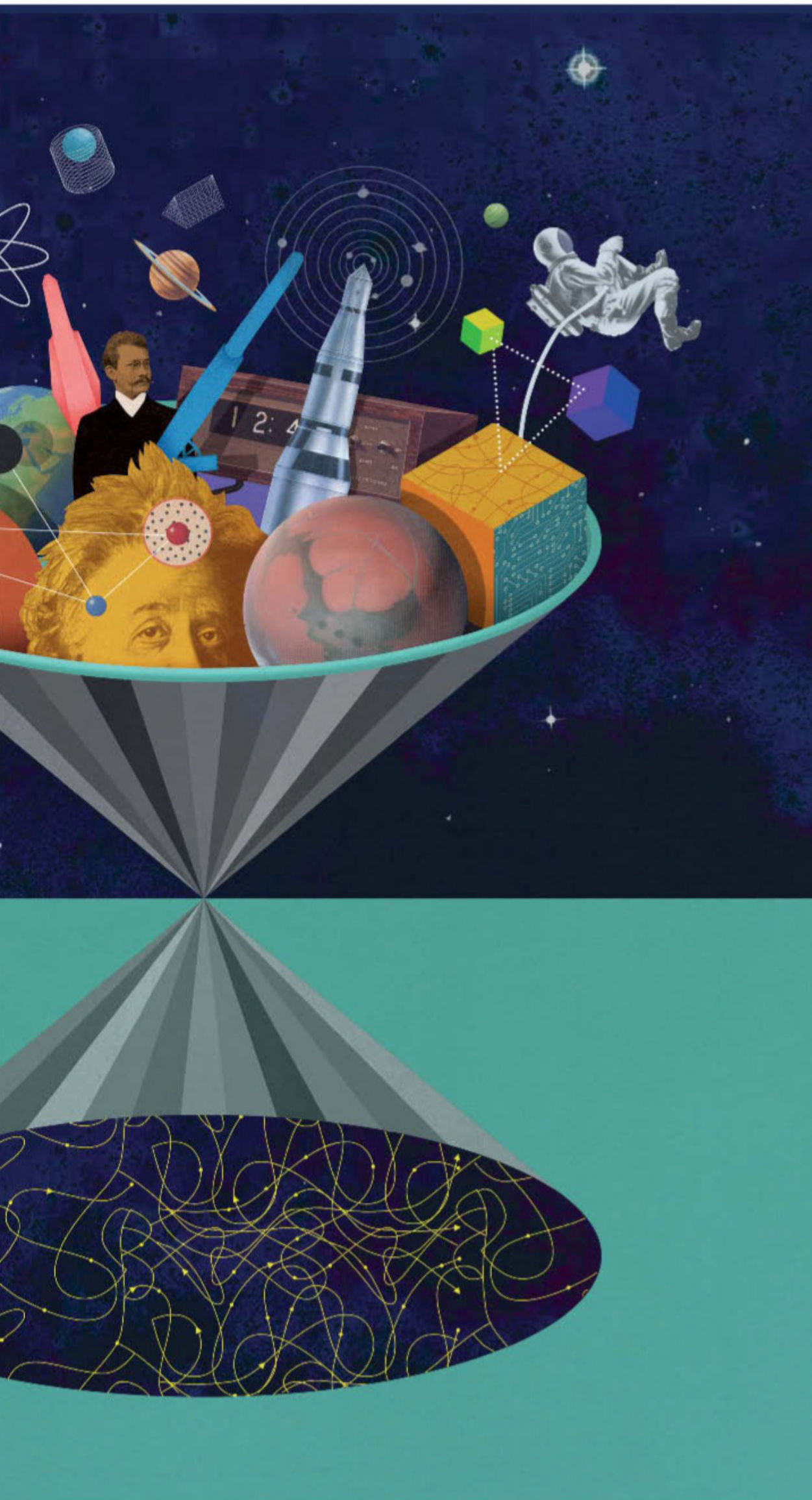
Space-time is a relatively new notion. Isaac Newton had no need for it. For him, space and time were individually real and absolute. Only when Einstein formulated his special theory of relativity in 1905 did the two start to come together. He showed that different observers will generally divide space-time into “space” and “time” in different, incompatible ways; what is “space” and what is “time” are relative to how an observer is moving.

Various thinkers had previously speculated that the two should be rolled together. In Edgar Allan Poe's 1848 prose poem *Eureka*, for instance, he wrote that “space and duration are one.” But it wasn't until 1908 that mathematician Hermann Minkowski unified them in a scientific way. He dramatically proclaimed: “Henceforth, space for itself, and time for itself, shall completely reduce to a mere shadow, and only some sort of union of the two shall preserve independence.”

Einstein was unimpressed, grumbling about “superfluous learnedness”. But he eventually came round to the idea, putting the geometry



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“How in the world can space-time exist in a superposition of various possibilities?”

of space-time firmly at the heart of his general relativity. It said that space-time isn't merely a static background in which things happen. It is a dynamic entity, warping and stretching under the influence of mass and energy. The curvature of space-time manifests itself to us as the force of gravity.

Still, it would seem weird to ask what space-time is “made of” in classical physics. In general relativity, space-time changes over time in response to other stuff. But it is still a background, and a fundamental constituent of nature. It isn't made of anything; it just “is”.

The problems with that view started with the discovery of quantum mechanics, the rules that govern the behaviour of subatomic particles and fields. Scientists haven't been able to construct a quantum-mechanical theory of gravity as they have for the three other fundamental forces of nature. Part of the issue is technical: when we try to make classical general relativity into a quantum-mechanical theory using standard techniques, our equations blow up and we get nonsensical answers. But part of it is conceptual.

Quantum mechanics tells us that systems exist in superpositions of different measurable quantities like position and velocity. There is no such thing as “the position” of a quantum particle; there are many possible positions, ➤

ENTANGLED TIME

In the quest to figure out what lies behind the backdrop to reality we call space-time, we have begun to grasp how the space part can emerge from quantum entanglement (see main story). Time is a different story. But there is one way to derive the fourth dimension from the same phenomenon.

It was suggested back in 1983 by Don Page, now at the University of Alberta in Canada, and William Wootters at Williams College in Williamstown, Massachusetts. In quantum mechanics, if a system can be in various different states, we can add those states together in any combination to create new states, superpositions of the originals. An electron, for example, can be spinning clockwise or counterclockwise, but it can also be in a superposition of both.

With that in mind, consider a quantum system consisting of two subsystems: one is a clock and the other is everything else. Let the system as a whole evolve through time, so that the clock reads differently at each moment. Now take a series of such moments, say one per second, and add together all the specific quantum states at all the moments—all the ways the world actually was at each reading of the clock.

This gives you a new super-state, a superposition of individual states with specific clock readings and specific configurations of everything else. It doesn't evolve with time. But because this is a quantum system, the clock is entangled with the rest of the world. And if we were to measure the clock to see what it read, the rest of the system would instantly snap into whatever quantum state the original system had at that corresponding time.

In this way, time can appear to emerge even in an unchanging quantum state. The key is entanglement; all we need is a clock subsystem that is entangled with the rest of the universe in the right way. Time is just what your clock reads.

which take on definite values only when we observe them. How in the world can space-time exist in a superposition of different possibilities? That would make it impossible to say for sure that a certain event happened at a definite location in space and time.

Physicists of different persuasions have taken different approaches to constructing a solution in the form of a theory of quantum gravity. The most popular is string theory, which replaces particles with loops and segments of vibrating string. String theory successfully produces a quantum version of gravity, but not one that connects with our world in an obvious way. Nor does it resolve those fundamental conceptual problems. String theory's leading rival, loop quantum gravity, is an attempt to directly quantise general relativity. Loop proponents typically take the conceptual challenges of quantum gravity more seriously than their stringy colleagues, but the challenges remain.

This has led some physicists to take a step back and ask the question in a different way. The standard approach to developing a quantum description of some phenomenon,

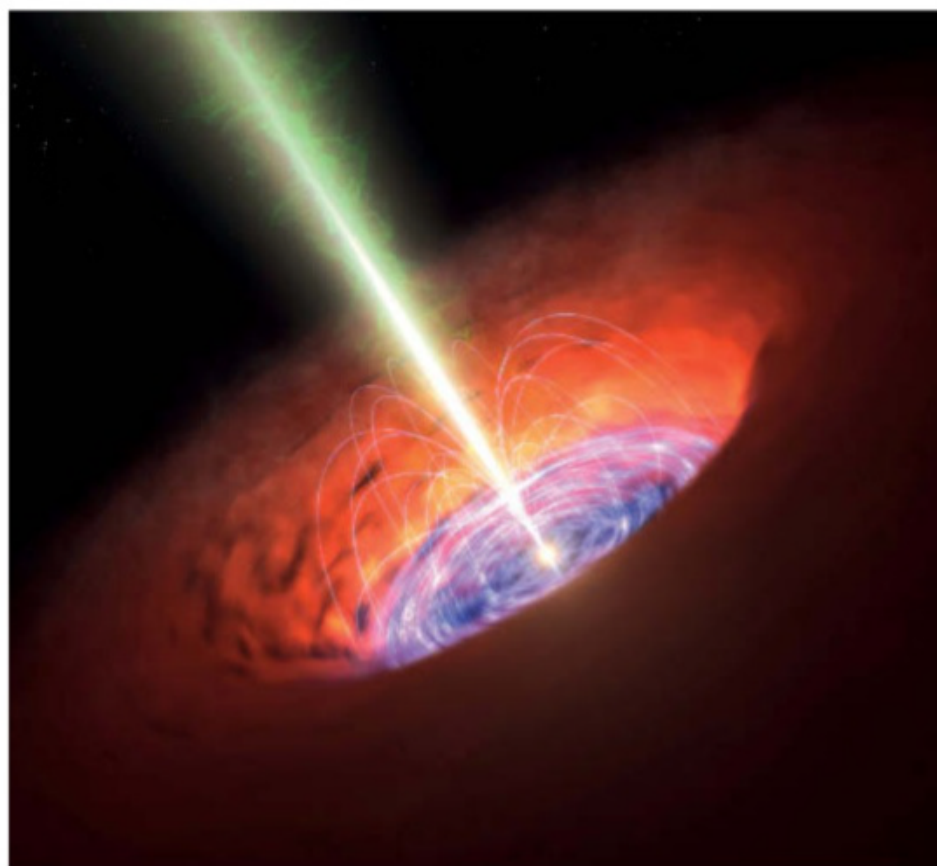
like the electromagnetic field or a collection of atoms, is to start with a classical description and then "quantise" it. That approach has failed again and again when it comes to gravity and space-time. It also isn't how nature works. The real world doesn't start classically and then somehow quantise. It is quantum from the start, and the classical world emerges as an approximation.

So maybe we shouldn't be trying to quantise gravity at all. Perhaps we should instead formulate a quantum theory from the start, and then show how classical space-time emerges from that. It is a new approach that has dramatic consequences for how we think about what space-time itself is made of.

Spooky action

To make progress in this direction, it is helpful to start with our current best physical theory, which is quantum field theory. According to this theory, the fundamental ingredients of the world are fields, such as the electric and magnetic fields. Even particles like electrons and quarks are simply vibrations

“Maybe it was a mistake to quantise gravity, and space-time was lurking in quantum mechanics all along”



Black holes give us reason to think space can emerge like a hologram

in fields that stretch through space.

Classically, we can specify the value of a field in an approximate fashion by dividing space into tiny regions, then listing the value of the field in each region. Once we graduate to quantum field theory, an extra feature comes into the game: the values of the field in different regions can be entangled with each other. Due to quantum uncertainty, we don't know exactly what answer we will get if we measure the field at some location, but entanglement means the answer we get at one point will affect what we would measure at any other point.

In the vacuum state of an ordinary quantum field theory – empty space, no particles flying around – the entanglement between fields in different regions is directly tied to the distance between them, and therefore to the geometry of space-time. Nearby regions are highly entangled with each other, while faraway regions share little entanglement.

This suggests an intriguing way to reverse our normal way of thinking and so find space-time within quantum theory. Let us imagine starting with just a quantum state, no pre-existing notion of space-time. Now we can try to work backwards, to extract space-time from entanglement.

If in ordinary physics the entanglement between two regions goes down as the regions get further apart, let us imagine defining the distance as (inversely) related to the entanglement. In that case, having a quantum state automatically gives us the “distance” between any two parts of it, and therefore defines a geometry on this emergent space.

So far so good. But a quantum state exists at each moment of time, so at best it can define the geometry of space at that moment. We want to extend this to four-dimensional space-time.

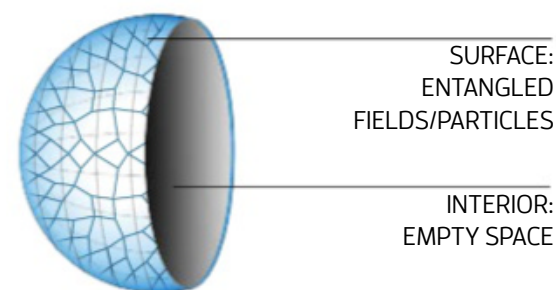
Thankfully, here we can borrow a trick from physicist Ted Jacobson at the University of Maryland, who, in 1995, showed how we could derive Einstein's equation for general relativity from simple assumptions about the relationship between entropy and geometry.

Entropy, a measure of disorder, is directly related to entanglement: the more entangled a region is with the rest of the world, the more entropy it contains. Einstein said that it is adding matter or energy to a region that causes space-time to curve. Jacobson showed that increasing the entanglement of a region can have the same effect, if we insist that the amount of entropy must be proportional to the area bounding that region. That is automatically true in empty space, but Jacobson suggested that it remains true even

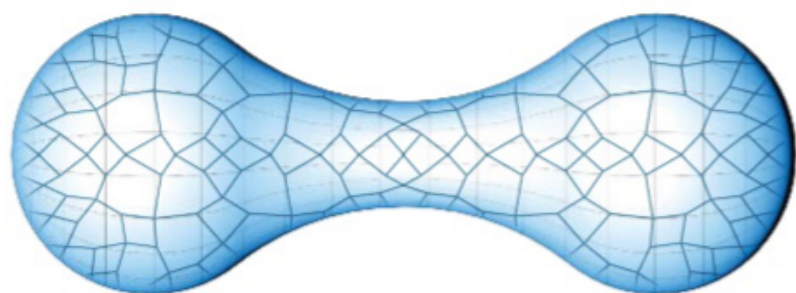
Quantum gum

Space-time might be woven from quantum entanglement

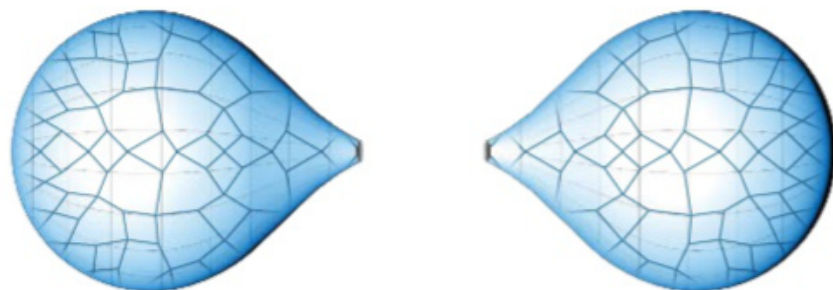
In a model universe, the equations describing gravity in a volume of space are equivalent to those describing the surface of that volume, which don't include gravity. This suggests space on the inside somehow emerges from the properties of the outside, namely entanglement



Sure enough, when you reduce the entanglement connecting two regions of the outside surface, the space inside pulls apart as if pulling at two ends of a piece of chewing gum



If you eliminate all entanglement, the space inside splits in two, suggesting that entanglement is the thread that binds space-time



when space isn't empty. You can try to add more entanglement, but space-time will bend to compensate, so that entropy always remains proportional to area.

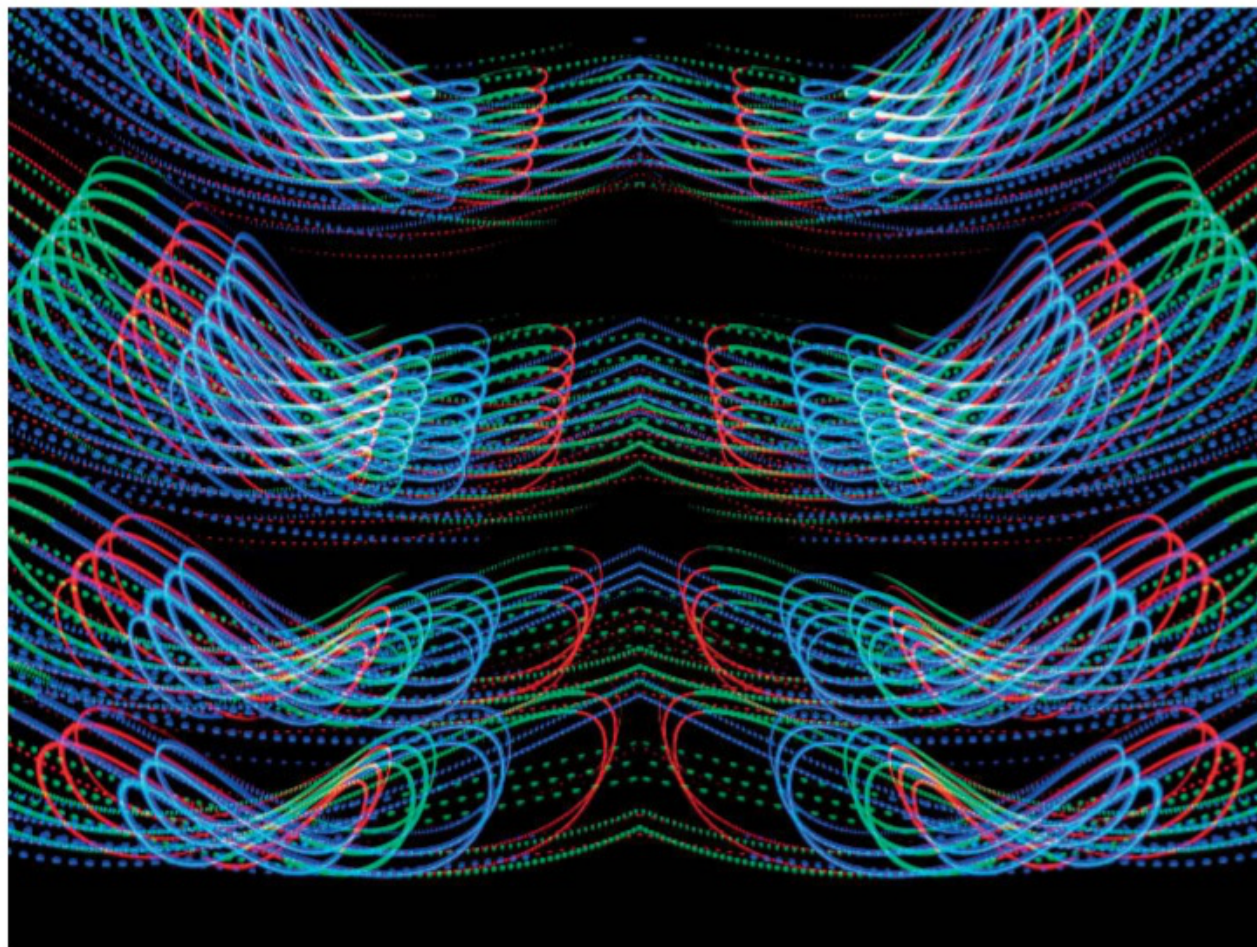
Essence of reality

So Einstein says that energy causes curvature, while Jacobson says entanglement does. But Jacobson also argued that it is really the same thing: whenever you add entanglement, energy necessarily follows. From this logic, he was able to derive that the curvature of space-time in his approach obeyed the same equation that Einstein first wrote down for general relativity. Gravity, it appears, can arise from entanglement, rather than directly from mass and energy. This remarkable result was the beginning of what is now called “thermodynamic” or “entropic” gravity.

But it doesn't quite get us to where we need to be. In deriving his alternative picture of where gravity comes from, Jacobson assumed

a classical space-time and imagined that there were quantum fields living within it. Ideally, we would like to keep everything quantum from the start and derive the existence of space-time itself. This is something I recently attempted with my collaborators, ChunJun (Charles) Cao and Spiros Michalakis at the California Institute of Technology. Rather than starting with vibrating quantum fields living in space-time, we started with completely abstract quantum “degrees of freedom”.

This is just some quantity that can take on different values, independently of other quantities. In Newtonian mechanics, the degrees of freedom are positions and velocities of particles; in field theory, they are the values and rates of change of the fields. In our approach, the degrees of freedom don't have any direct physical interpretation. They are the basic stuff of reality, the essence out of which everything else is made – a kind of “quantumness” that pre-exists everything. Most importantly, these quantum degrees



Ethereal connections between distant quantum elements could hold the cosmos together

“Only with massive amounts of entanglement do we see large-scale distortions in the fabric of space”

of freedom are entangled with each other.

With that in mind, we flip around Jacobson’s idea. Now we can define the area surrounding a region as the entanglement of its degrees of freedom with the outside world. And sure enough, the corresponding geometry obeys Einstein’s equation of general relativity. Gravity, in other words, can emerge directly from the quantum essence of reality, without quantising any assumed classical stuff.

That might sound like a conclusion, but it is more like a promising beginning. Many assumptions went into our derivation, and whether these assumptions hold true in nature remains to be seen. Most importantly, our derivation of Einstein’s equation from entanglement only works when gravity is weak and spacetime is nearly flat. Once gravity becomes strong and space-time is curved, as in the Big Bang or near a black hole, radically new phenomena become important.

The most dramatic of these is the “holographic principle,” the idea that the degrees of freedom describing a black hole

can be thought of as living on its edge, the event horizon, rather than the interior. Juan Maldacena of the Institute for Advanced Study in Princeton used the holographic principle to show an equivalence between two very different theories: quantum field theory without gravity in four-dimensional space-time, and quantum gravity with a negative vacuum energy in five dimensions.

The wormhole connection

Subsequent work by Mark van Raamsdonk at the University of British Columbia in Canada and others has shown that the space-time geometry on the quantum-gravity side of this correspondence is directly tied to quantum entanglement on the field-theory side. As we decrease entanglement in the field theory, space-time on the quantum-gravity side grows apart (see “Quantum gum”, page 37).

Maldacena and Leonard Susskind at Stanford University in California have taken this connection to extremes with a bold idea

they dubbed “ER=EPR.” ER stands for Albert Einstein and Nathan Rosen, who wrote a paper in 1935 proposing the existence of wormholes, or shortcuts through space-time. EPR, meanwhile, stands for Einstein, Boris Podolsky and Rosen, who collaborated on another paper emphasising the role of entanglement in quantum theory. The ER=EPR conjecture therefore posits that whenever you have two entangled particles, there is a tiny wormhole connecting them.

Don’t take this too literally. The wormholes that purportedly connect pairs of particles would be microscopically small and impossible for anything to pass through. It is only when massive amounts of entanglement become involved that we begin to see a macroscopic distortion in the fabric of space.

Moreover, our universe has a positive vacuum energy, not a negative one, so the implications of the equivalence revealed in Maldacena’s negative-vacuum-energy thought experiment don’t translate directly to an actionable strategy for dealing with quantum gravity in the real world. They do, however, serve as another strong hint that quantum entanglement is at the heart of it all.

All of these ideas are, at present, somewhere between promising conjectures and optimistic dreams. We don’t know the best way to think about these supposed fundamental degrees of freedom that entangle together to make space-time, nor do we know how they interact with each other in any detailed way. We can’t yet derive the emergence of quantum fields living within space-time, obeying the rules of relativity. And we certainly can’t answer important questions like why the energy of empty space is so small, or why space has four macroscopic dimensions.

Even so, imagining that space-time emerges from quantum entanglement is a promising way to think about the basic nature of reality. It may be that it was a mistake to start with general relativity and try to quantise it; maybe space-time was lurking within quantum mechanics all along.

And even if formulating a complete theory of quantum gravity isn’t your thing, thinking about space-time this way should at least put a new slant on the familiar four-dimensional continuum in which we live, rushing around in space to be on time for coffee. ■